Design and Control of a CT-Compatible Needle Steering System

Navid Shahriari

Edsko E. G. Hekman

Sarthak Misra

MIRA-Institute for Biomedical Technology and Technical Medicine,
University of Twente, The Netherlands

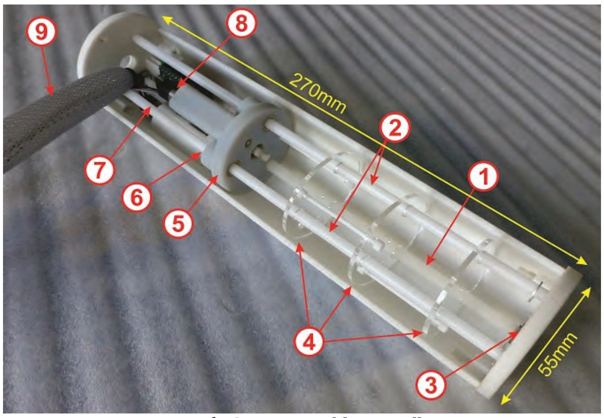

Figure 1. Prototype of CT-compatible Needle Insertion Device, ①-drive shaft ②-guide bars ③-insertion point ④-supporting discs ⑤-carriage ⑥-bushing ⑦-insertion/retraction motor ⑧-rotation motors ⑨-cables to the control board.

1 Introduction

Image-guided minimally invasive interventions such as biopsies, brachytherapies and ablations are well-established procedures. Typically, such procedures require insertion of a needle into the body. The goal is to reach the cancerous or suspicious lesion accurately. To achieve this goal, different imaging modalities such as ultrasound, computed tomography (CT), magnetic resonance imaging (MRI) and fluoroscopy are used as feedback.

Insertion and manipulation of the needle is done manually in current clinical practice. However, extensive research has been done which aims at developing methods to perform these procedures using robotic setups to benefit from their precision.

One of the important topics in this field is cancer related diagnoses and therapies of lung, because lung cancer is the most common cause of cancer related death worldwide (1.59 million death in 2012) [1]. Early detection is very important to reduce mortality rates [2]. After a suspicious lesion is observed in CT images, usually a needle biopsy is performed, and the sampled tissue is tested to confirm the diagnosis. One of the main challenges involved in these interventions is that the lesion moves due to respiration. Therefore, patient compliance and clinician's skill are important factors for a successful procedure. Different robotic setups has been developed to improve interventional accuracy and to make it less dependent on the clinician's skills [3].

It is possible to categorize the robotic setups into different groups based on their insertion principle and the structure they use. Some of these setups are only positioning devices [4]. After the best insertion pose is determined, the device places a needle holder in the proper position and orientation and then needle insertion is done manually. On the other hand, there are Needle Insertion Devices (NID), which not only position the needle, but also perform the insertion [5]. Also, the positioning device or NID could be patient-mounted, bed-mounted or could have its own base. While patient-mounted devices compensate for the body motion (due to respiration, fluid flow and etc.), bed-mounted and base-mounted devices need to track the chest motion and compensate for it in the control scheme. In this work, we are interested in developing a test bed to be used in lung and liver biopsies using CT images.

2 Design

As mentioned earlier, our objective is to design a portable NID which could be used with an ultrasound system in the laboratory during our research, and within a CT scanner for *in-vivo* tests. Subsequently, the robotic system needs to be CT-compatible and compact enough to fit into the CT bore. Considering different Siemens CT scanners, the bore is about 78cm in diameter. When a patient is inside the bore, there is about 30cm free to place the device.

After studying different robot architectures, we concluded that our robot for the specific task of lung and liver biopsy, and also similar tasks, should have at least four degrees of freedom (DoF). It must consist of two rotational DoF around the entry point, plus two degrees of freedom (one rotational and one translational) for needle steering. In addition the device should be small enough, portable and light weight, to be placed on the patient in the CT scanner.

This study is focused on the steering mechanism and the issues involved in the design. As depicted in Figure 1, the total device is 55mm in diameter and 270mm long. The needle is attached to the carriage using a chuck mechanism. This prototype is designed to be used with the needles of 150mm length and the maximum insertion depth is 120mm. There are threads inside the contact hole of carriage with the drive shaft. Therefore, the carriage is pushed forward and backward (insertion / retraction) by rotating the drive shaft. The two guide bars are to constrain the motion of the carriage in other directions than insertion/retraction and enable a smooth motion. Since the force by the drive shaft is not symmetrically applied to the carriage, there are forces realized in the contact points of the carriage and the guide bars which introduce friction against the motion. Therefore, two oil free bushings are placed in the carriage (Figure 1, ⑥) to reduce this friction. Also, the guide bars and the drive shaft are made out of Delrin which has self-lubrication properties to reduce the friction.

Two motors are used to control the two degrees of freedom. One is used to rotate the needle along its axis and the other one is used to insert the needle into the tissue. The motors are brushed-DC 1016N012G with a HEM-3 quadrature encoder and a 10/1 planetary gearhead of 1:4 ratio (Faulhaber Group, Schönaich, Germany). In order to transfer the motor torque to

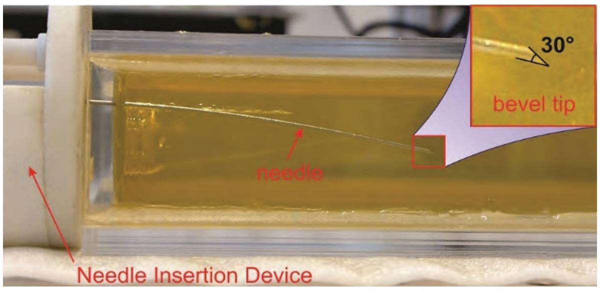

Figure 2. Representative steering result with 0% duty-cycling (maximum reachable bend) and 1mm/s insertion speed.

needle holder, 1:3 ratio spur gears are used. Choice of motors parameters and transfer ratios were calculated considering the force/torque needed to steer the needle, the maximum insertion and rotation speed and finally space limitations.

The motors are controlled using proportional-integral-derivative (PID) controller which was implemented using an ATMEGA328 microcontroller. The feedback for the PID controller is based on the motor encoders. The motors speeds are controlled through Pulse Width Modulation (PWM).

One of the issues in needle steering using flexible needles is that the needle buckles if there is no support around it during the insertion. To overcome this problem, we have designed a disc mechanism which supports the needle and is pushed forward and backward with carriage.

3 Control and Steering Experiments

In order to test the proposed system, we use beveled-tip flexible needles made of nitinol. The needles are made from the nitinol rods with a diameter of 0.5, 0.75, 1.00 and 1.50mm and with bevel angles of 30, 45 and 60 degrees. The asymmetry of the needle tip cause the needle to bend while being inserted into the tissue because of asymmetric forces applied to the needle tip [6]. Smaller bevel angles cause more maneuverability of the needle in the tissue. In our experiments we have realized that the best choice of system parameters to reduce the target motion is 1mm diameter needle with insertion speed of 1mm/s and bevel angle of 30 degrees. As a result, we are using these values in the experiments.

In the experiments, gelatin phantoms were made by mixing 14.9% gelatin powder (Dr. Oetker, Ede, The Netherlands) with 85.1% water. This mixture will result in a transparent phantom with an elasticity of 35 kPa which mimics the properties of soft biological tissue. The steering was performed using duty-cycling [7] and with duty-cycles of 0%, 50% and 100%. Figure 2 provides a representative result.

4 Ongoing Work

This study presents the design and control of a CT-compatible needle steering system. The device has two DoF, which one is used for needle insertion and retraction and the other is used for needle rotation. The insertion is achieved by rotating the drive shaft which cause the carriage to move forward and backward due to the threads inside the carriage. The rotation is achieved by transferring the motor torque to the needle holder using spur gears. The motors are controlled using PID controller and the reference motor speed is achieved using PWM.

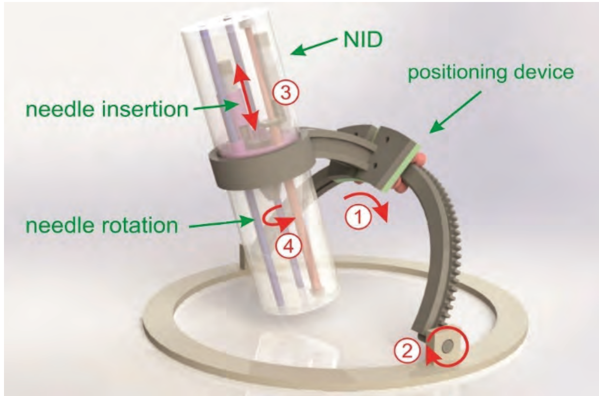

Figure 3. Complete CT-compatible Needle Insertion Device (NID), providing two DoF around the entry point ①-② and two DoF for steering ③-④.

The preliminary experiments prove the design concept. The setup has been used to steer beveled-tip nitinol needle of 1mm diameter in 14.9% weight gelatin phantom. The insertion was done successfully and no buckling was observed.

The ongoing work is focused on more realistic experiments in CT scanner to prove the compatibility of proposed device. Also, we are designing two different positioning devices for the proposed NID. The first one is an actuated patient mounted holder, which could rotate the NID around the entry point (Figure 3). This will help us to study the effect of base motion on the steering. The second one is a passive holder which is used to make an inclination between the NID and CT image plane to reduce the interference.

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